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The influence of fuel composition on the combustion and emission characteristics of natural gas fueled engines

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ABSTRACT

As global energy demand rises, natural gas (NG) plays an important strategic role in energy supply. Natural gas is the cleanest fossil fuel that has been investigated extensively for use in spark-ignition (SI) and compression-ignition (CI) engines. This paper reviews the research on the effects of natural gas composition on combustion and emission characteristics of natural gas fueled internal combustion engines (ICEs) and reports the most achievements obtained by researchers in this field. It has been reported that the engine performance and emission are greatly affected by varying compositions of natural gas. The most important NG fuel property is the Wobbe number (WN). Generally, it was agreed by researchers that the fuels with higher hydrocarbons, higher WN, and higher energy content exhibited better fuel economy and carbon dioxide (CO_2) emissions. Nitrogen oxides (NO_x) emissions were also increased for gases with higher levels of higher WN, while total hydrocarbons (THCs), carbon monoxide (CO), showed some reductions for these gases. On the other hand, particulate matter (PM) emissions did not show any fuel effects. Moreover, adding of small fractions of higher alkanes, such as ethane and propane, significantly improved ignition qualities of natural gas engines. The results presented provide a good insight for researchers to pursue their future research on natural gas fueled ICEs.

Contents

1. Introduction

In recent years, shortages of crude oil, increasing of fossil fuel prices and the tightening of environmental regulations have led to development of alternative fuels application in internal combustion engines. Natural gas is one of such fuels available in large quantities in many parts of the world at attractive prices. Natural gas consumption is forecasted to be doubled between 2001 and 2025, with the most robust growth in demand expected among the developing nations [1]. As shown in Fig. 1, the share of NG has been progressively increased within the energy market in the past three decades [2]. Natural gas is a potential alternative to conventional liquid fuels (i.e. gasoline and diesel) for use in automotive engines [3–7]. Natural gas is a mixture of various hydrocarbon molecules. Commercial natural-gas compositions vary from 85% to 96% methane. NG also contains heavier hydrocarbons such as ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}), and inert diluents such as molecular nitrogen (N_2) and carbon dioxide (CO_2). Sulfur compounds and other hydrocarbon species are also available within NG.

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Nomenclature

Greek

φ	equivalence ratio

Abbreviations

SI	spark ignition
CI	compression ignition
NG	natural gas
ICE	internal combustion engines
THC	total hydrocarbon
NO_x	nitrogen oxides
PM	particulate matter
NMHC	non-methane hydrocarbons
HCHO	formaldehyde
CNG	compressed natural gas
NGV	natural gas vehicles
WN	Wobbe number
MN	methane number
CARB	California air resources board
RPM	revolutions per minute
WOT	wide open throttle
EGR	exhaust gas recirculation
EOBE	effective on-board energy
TWC	three-way catalyst
PN	particle number
CP	combustion potential
HHV	higher heating value
LHV	lower heating value
SG	specific gravity
IANGVs	international association for natural gas vehicles
LPG	liquefied petroleum gas
HCCI	homogeneous charge compression ignition
A/F ratio	air–fuel ratio
SOC	start of the combustion
TDC	top dead center
NH_3	ammonia
CA	crank angle
BSFC	brake specific fuel consumption
BMEP	brake mean effective pressure
DI	direct injection
IDI	indirect injection
DF	dual fuel
RTC	refuse truck cycle
CBD	central business district
FTP	federal test procedure
DME	dimethyl ether

The geographical source, time of year, and treatments applied during production or transportation have great influence on levels of these species [8–12]. The typical composition of natural gas in percentage is illustrated in Fig. 2. Therefore, natural gas does not describe a single type of fuel or a narrow range of characteristics.

Natural gas is a clean burning fuel as compared to the conventional liquid fuels like diesel or gasoline. It has a high octane number and therefore it is suitable for engines with relatively high compression ratio. It has a high self-ignition temperature, so it requires intense source of energy to enable combustion, i.e. glow plug, spark plug or pilot liquid fuel. It mixes rapidly with air to form homogenous air fuel mixture for efficient combustion inside engine cylinder and substantial reduction in harmful emissions [13,14]. A number of research works have been conducted in the literature on utilization of natural gas in SI and CI engines. Comparing natural gas and diesel engine emissions, it was found that natural gas fueled SI engine emissions of total hydrocarbon (THC), nitrogen oxides (NO_x), and particulate matter (PM) were significantly lower than that of the diesel fueled engine. In addition, another study showed that natural gas SI engines have the potential to achieve a reduction in carbon monoxide (CO), CO_2, NO_x, and non-methane hydrocarbon emissions compared to gasoline engine emissions [5,15–18]. The number of compressed

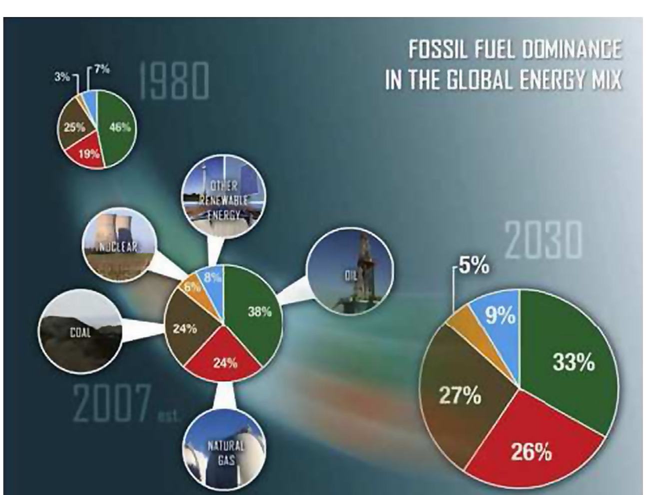


Fig. 1. The share of World energy, past, present and future [2].

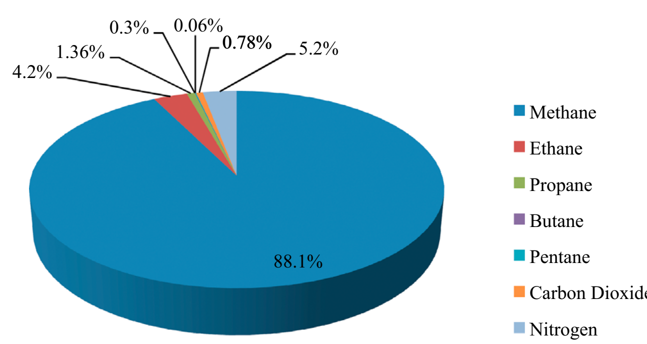


Fig. 2. Typical natural gas composition by volume.

Table 1
Properties of natural gas, gasoline and diesel fuels [18].

Fuel property	Gasoline	Diesel	CNG
Chemical formula	C_4–C_{12}	C_4–C_{12}	CH_4
Molar mass (g/mole)	114	170	19
Carbon content (%)	85	86	75
Hydrogen content (%)	15	14	25
Oxygen content (%)	0	0	0
Carbon-to-hydrogen ratio	0.54	0.516	0.25
Cetane number	5–20	40–50	–
Octane number	86–94	–	> 120
Auto-ignition temperature (K)	533	483	853
Stoichiometric air/fuel mass ratio	14.7	14.6	17.2
Boiling point at 1 atm (K)	300–498	450–643	111.4
Lower heating value (MJ/kg)	43.44	42.5	47.14
Liquid density (kg/m3)	737	831	465

natural gas (CNG) vehicles is continuously growing, and old vehicles are being converted into CNG vehicles through engine modifications. Globally, natural gas powers about 15.2 million vehicles worldwide. Natural gas vehicles (NGVs) running on CNG are appropriate cases for high-mileage, centrally-fueled fleets that operate within a limited area [19]. Table 1 lists the properties of natural gas, gasoline and diesel fuels [20]. Typical combustion properties of natural gas are given in Table 2 [21].

Due to the fact that the various compositions of natural gas will affect the power and emission characteristics of vehicles, studying the effect of natural gas composition on performance and emission characteristics of natural gas fueled internal combustion engines become one of the utmost important research directions for engine researchers. The effect of fuel composition on the combustion process and on the emissions from natural-gas fueled engines has been addressed in both fundamental and applied studies. The majority of the research has been focused on lean burn spark-ignition engines, which are currently the predominant form of natural-gas engines. This paper deals with reviewing the research works on effect of natural gas composition in CNG engines, and reports most of the achievements obtained during the process in order to make them known to the world and identifies the challenges and opportunities for future research.

2. Natural gas composition

As mentioned before, natural gas is not a homogeneous mixture, but varies in composition which is highly dependent on the production area, season, and climate. Therefore its thermodynamics properties are dependent on its components. To obtain the thermodynamics properties accurately, the effect of the gas compositions must be also considered. Table 3 demonstrates the mole fraction of natural gas extracted from various region of Iran. Variations occur between the originating fields and may be attributed to the processing prior to transmission. Moreover, additional mixing of different gases occurs during pipeline transmission [22,23].

Table 2
Typical combustion properties of natural gas [19].

Ignition point	876 K
Theoretical flame temperature (stoichiometric air-to-fuel ratio)	2233 K
Maximum flame velocity	0.3 m/s
Water vapor content	16–32 mg/m^3
Sulfur content	5.5 mg/m^3
Higher heating value (dry basis)	36.0–40.2 MJ/m^3

Table 3
Mole fraction of natural gas extracted from various region of Iran [22].

Component	Mole fraction (%)			
	Khangiran	Kangan	Pars	Bidboland
CH_4	98.6	90.04	87	85.01
C_2H_6	0.59	3.69	5.4	9.38
C_3H_8	0.09	0.93	1.7	3.49
i-C_4H_{10}	0.02	0.2	0.3	0.34
n-C_4H_{10}	0.04	0.29	0.45	0.65
i-C_5H_{12}	0.02	0.14	0.13	0.1
n-C_5H_{12}	0.02	0.08	0.11	0.09
n-C_6H_{14}	0.07	0.14	0.07	0.09
C_7^+	0	0.01	0.03	0
N_2	0.56	4.48	3.1	0.44
CO_2	0	0	1.85	0.41

The performance and emissions of gas engines depend on good ignition, optimum combustion rate, high knock resistance, and a sufficient energy content of the fuel mixture. Some fuel properties such as density, heating value, the stoichiometric air–fuel ratio and knock resistance are important in relation to engine performance when using natural gas as a fuel. Current research on the natural gas vehicles found that the engine performance and emission are greatly affected by varying compositions of natural gas. It was also reported that the heating value, efficiency, and concentration of un-burnt hydrocarbon and other emission particles would highly depend on the source of supply of natural gas as the main fuel [24,25]. Ly [26] also mentioned that this effect is especially dominant in heavy-duty engines with high compression ratio applications due to the increased amount of engine “knocking”.

The two primary factors that affect emissions and directly describe the general characteristics of natural gas include the methane number and the Wobbe number (WN) or Wobbe index (WI). The methane number (MN) is a good measure because it is the dominant component in natural gas. In addition, the anti-knock property of natural gas fuel can be expressed as methane number. Pure methane has a methane number of 100, and pure hydrogen has a methane number of 0. The methane number of the mixture is defined as the percentage of methane in a methane–hydrogen mixture. This is similar to the scale used for octane number of gasoline. Octane number is not an appropriate scale for natural gas since the octane scale only goes up to 120, and methane has an octane number in excess of 120. Since, the methane number of various natural gas compositions can vary considerably, there may be a problem with knock in some engines [27]. The determination of the methane number of a fuel is conducted under a prescribed engine test. During the test, the compression ratio of the engine is increased until knock is detected. Mixtures of methane and hydrogen are then run into the engine. The mixture that produces knock at the same compression ratio as the fuel being tested determines the methane rating of that fuel. The time and cost associate with performing the test makes this approach impractical. Two mathematical alternative methods to determine methane number of the gas composition are the California air resources board (CARB) method and Anstalt für Verbrennungskraftmaschinen (AVL) method. The AVL method uses a proprietary program to calculate methane number, but the CARB method uses the following equations [28,29]:

$$\mathrm{MON} = 406.14 + 508.04(H/C) - 173.55(H/C)^2 + 20.17(H/C)^3 \tag{1}$$

$$\mathrm{MN} = 1.624 \times \mathrm{MON} - 119.1 \tag{2}$$

The WN is a measure of the fuel energy flow rate through a fixed orifice under given inlet conditions. It is calculated as the ratio of the heating value divided by the square root of the specific gravity. Variations in WN of the gas will produce similar variations in the air–fuel ratio for gas metering systems used on vehicles. Generally, the WN is a good criterion for natural gas because it correlates well with the ability of an internal combustion engine to use a particular gas. It also takes into account many of the gas components because it is a bulk property [25].

Values for WI and the combustion potential (CP) have been calculated using Eqs. (3) and (4), where the CP is a value that can provide the theoretical burning velocity of a mixed gas based on the burning velocity of hydrogen.

$$\mathrm{WI} = \frac{\mathrm{LHV}}{\sqrt{\mathrm{SG}}} \text{ or } \mathrm{WN} = \frac{\mathrm{HHV}}{\sqrt{\mathrm{SG}}} \tag{3}$$

$$\mathrm{CP} = k\frac{\mathrm{H_2} + 0.6(\mathrm{CO} + \mathrm{C}_m\mathrm{H}_n) + 0.3\ \mathrm{CH_4}}{\sqrt{\mathrm{SG}}} \tag{4}$$

k is correction factor adjusted by the O_2 concentration in the fuel. In Eqs. (3) and (4), lower heating value (LHV) and specific gravity

(SG) denote the lower heating value and specific gravity of the gas, respectively [30].

3. Implication of natural gas composition in ICEs

Currently, more than 17 million NGVs and about 20,000 stations exist worldwide and NGV Global (IANGV) is projecting that this will increase to 50 million vehicles by 2020 with annual growth rate of 3.7%. Natural gas is the second most widely used alternative fuel (after LPG). With annual growth of approximately 25% from 2001 to 2011, transportation use of natural gas is increasing in both established and new markets. By the end of 2012, Iran had the world's largest fleet of NGV at 3.30 million vehicles [14,31].

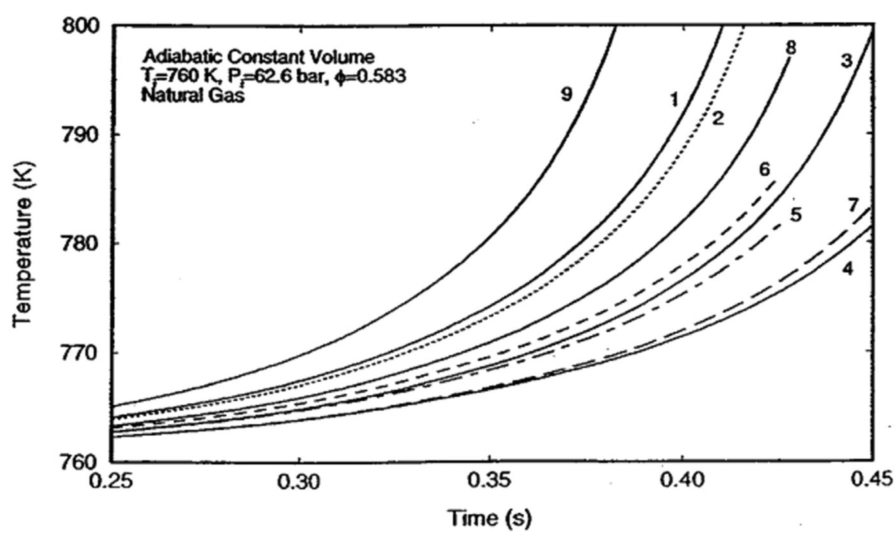
NGVs can be dedicated to natural gas as a fuel source or they can be bi-fueled, running on either natural gas or gasoline, or natural gas or diesel. Because most natural gas engines are spark-ignited, the usual bi-fuel pairing is natural gas and gasoline. NG engine technologies differ in the method used to ignite the fuel in the engine cylinders, the air–fuel ratio, the compression ratio, and the resulting performance and emissions capabilities. Various types of natural gas engine technologies have been developed including spark-ignition stoichiometric, spark-ignition lean burn, compression-ignition dual-fuel (with diesel for pilot ignition) and homogenous charge compression ignition (HCCI) engines [32–35]. The detailed information about natural-gas fueled spark-ignition and compression-ignition engines can be found in Ref. [11].

Khalil and Karim [36] studied the effect of variations in the composition of natural gas on the ignition and combustion processes in engines with emphasis on changes in the relatively small concentrations of high molar mass alkanes that may be present in the fuel. They found that the presence of small concentration of n-heptane with methane can produce very substantial changes in its auto-ignition and combustion characteristics. Fig. 3 shows the relative variations in the reactivity of the different natural gases. It is apparent that the fluctuations in their composition produce different levels of reactivity leading to auto-ignition. The composition designated as No. 9, produced the fastest reactions, while No. 4 had the lowest. A comparison of the relative reactivity of the fuel mixtures showed that although the relative concentration of methane varied by only two percent, the reactivity of these fuel mixtures varied very significantly as a result of the variations in the concentrations of their other components indicating the important role played by these higher hydrocarbons.

According to the literature review, all of the research done on investigating natural gas composition effects on ICEs have been conducted on SI, CI, dual fuel and HCCI engines.

3.1. Natural gas composition effects in SI engines

The earliest research on implication of natural gas composition in SI engines should be traced back to the middle of 1980s, when natural gas was employed as the secondary fuel in gasoline engine. Elder et al. [37] carried out experimental and theoretical investigations at the University of Auckland to determine the effects of varying fuel compositions on vehicle fuel consumption, power output and pollutant emissions. They conducted the experiments on a chassis dynamometer over the urban cycle of NZS 5420:1980 at steady speeds of 50 km/h and 80 km/h and at a number of engine speed and power conditions. For the two LPG fuels used, with compositions varying between 64% and 94% propane, they observed little difference in vehicle power output and fuel



	1	2	3	4	5	6	7	8	9
N_2	4.83	5.42	0.84	3.53	3.91	3.91	2.56	2.49	4.32
CH_4	86.16	86.00	89.96	88.34	87.81	87.61	88.74	87.99	85.26
CO_2	1.14	0.98	1.41	1.08	1.07	1.23	1.28	1.42	1.45
C_2H_6	5.43	5.47	5.38	5.27	5.30	5.30	5.64	5.82	6.06
C_3H_8	1.70	1.58	1.92	1.29	1.36	1.29	1.39	1.67	2.13
i-C_4H_{10}	0.19	0.18	0.13	0.13	0.16	0.17	0.11	0.16	0.19
n-C_4H_{10}	0.30	0.31	0.28	0.21	0.24	0.28	0.18	0.29	0.35
i-C_5H_{12}	0.08	0.08	0.00	0.05	0.06	0.07	0.04	0.06	0.08
n-C_5H_{12}	0.08	0.08	0.03	0.04	0.05	0.07	0.04	0.06	0.07
C6+	0.10	0.09	0.01	0.06	0.06	0.08	0.04	0.05	0.09
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Fig. 3. Variation in the temperature–time development for the various natural gas compositions [36].

consumption. For the two CNG fuels used, with compositions varying between 81% methane and2.5% CO_2, 2.3% N_2 and 73% methane, and 12% CO_2 and 2.7% N_2 there were significant differences in many aspects of vehicle performance. King [38] analyzed the impact of natural gas fuel composition on fuel metering and engine operational characteristics. He developed a fuel metering model to analyze the impact of fuel composition on carbureted, premixed, and direct-injected engine configurations. The change in physical properties of the fuel was found to have a profound effect on fuel metering characteristics. He found that fuel composition affects different fuel metering configurations differently, but these variations were minor compared to the fuel property effects. Moreover, he reported that fuel composition also affects the lean-flammability-limit of the mixture which, when combined with fuel metering variations, can cause a lean-burn engine to misfire. Also, fuel temperature variations affected fuel metering and must also be considered. The results indicated that closed-loop mixture control is essential for stoichiometric engines and very beneficial for lean-burn engines.

Thiagarajan et al. [39] experimentally investigated effect of varying gas composition on the performance and emissions of a SI engine. The pipeline natural gas composition was varied by adding volumes of propane (up to 20%) or nitrogen (up to 15%). They found that brake power, fuel conversion efficiency and before catalyst emissions of CO, NO_x and hydrocarbons were not affected by propane addition as long as stoichiometric combustion was maintained. In addition, nitrogen addition at the stoichiometric condition significantly reduced before catalyst NO_x emissions and increased after catalyst CO emissions.

A survey of the CNG compositions within NGV driving range of Houston was performed by Matthews et al. [40]. It was found that the statistics for the Texas CNGs were very similar to those from a previous national survey. In addition, two extremes of CNG composition were chosen for a study of the effects of composition on emissions, fuel economy, and driveability. They also investigated correlations for the relationships between the CNG composition and tailpipe emissions, fuel economy, and driveability. They stated that the most important fuel properties were the mass-based heating value, the energy density per cycle, the WN, the fuel methane-to-hydrocarbon percentage, and the product of the specific gravity and the mass-based heating value. They also showed that relatively small changes in the fuel CH_4/HC percentage can have a significant effect on the exhaust non-methane hydrocarbons (NMHCs) emissions, the NMHC/THC ratio, and the HCHO/NMHC ratio. It was also concluded that substitution of CNG for gasoline should produce a greenhouse benefit of $\sim$19%. At last, it was shown that the effects of CNG composition on driveability are minor.

In another research, the effect of natural gas composition on NO_x, flame structure and burning velocity was studied computationally by El-Sherif [41]. The results showed that an increase of ethane concentration in the natural gas leads to an increase in the lean flammability limit, burning velocity, CO and NO_x at very lean flames.

Lee and Kim [42,43] examined the effect of gas composition on vehicle performance such as fuel economy, driveability and exhaust emissions. Analysis was made using three types of NGVs which were manufactured by auto-makers and six different fuels which were selected in consideration of the variation in fuel composition on the worldwide market. These results might be utilized to develop natural gas engine in auto-maker. They found that fuel economy is proportional to lower heating value of stoichiometric unit mixture, and the difference between the highest and the lowest fuel economy due to fuel composition change was, relatively large, about 25%. Therefore, it is preferable to maintain the constant fuel composition at the refueling station. Also, they reported that gas composition variation has a negligible effect on vehicle driveability. In addition, effects of gas composition on CO, NO_x, CH_4 and THC emissions were contrast, then it is expected that design target or emissions standard may not be cleared because any emission is increased while the other is decreased when fuel composition is changed. Moreover, since stoichiometric A/F ratio varies with gas composition, it follows that actual A/F ratio might be shifted to fuel-rich or fuel-lean side which resulted in excess emissions penalty when the vehicle was optimized for a specific gas fuel. Therefore, it is preferable to design the engine parameters to compensate the variations of fuel composition or to limit the gas fuel composition at the refueling station in order to minimize exhaust emissions.

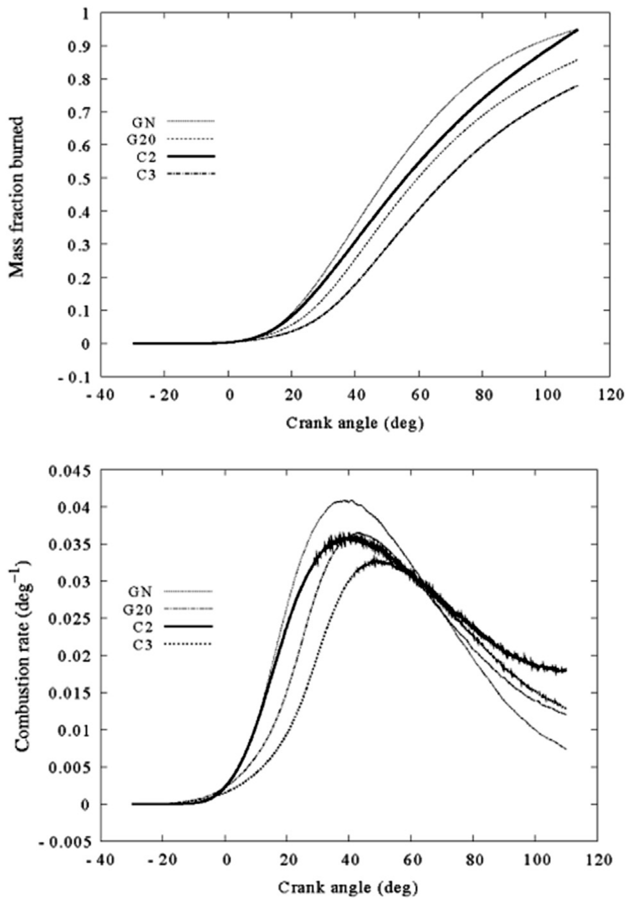
Min et al. [44] made experimental investigations to study the effects of the difference in gas composition on the engine performance and emission characteristics of a 1.5 L gasoline engine. The results indicated that THC decreases with increasing WI and CP. On the other hand, it is observed that NO_x slightly increases as WI and CP increase. They proposed the TLHV as a potential index for compatibility of gas fuels in a CNG engine.

Caillol et al. [45] presented the experimental results of a single cylinder spark ignition engine fueled with various natural gas compositions in lean mixture, and described a numerical model that accounts for variations in concentrations of the fuel components. Fig. 4 shows the numerical calculated mass fraction burned (x_b) and combustion rate ($dx_b/d\theta$) at lean equivalence ratio (φ=0.65) for the four compositions of fuels. As can be seen, for lean φ, the greater ignition delay period leads to retarding of start of the combustion (SOC) close to top dead center (TDC). The main combustion period is then delayed. The burning velocity is not enough to propagate the flame in the whole gaseous fuel–air mixture and, consequently, incomplete combustion may take place at exhaust valve opens. On the other hand, the presence of ethane has its greatest influence during the earliest stages of combustion. Their results demonstrated the beneficial effect of the combined presence of propane and ethane in the gas mixture on burning velocity in lean mixtures. Later, Caillol and Berardi [46] developed a simulation tool to analyze the influence of gas composition on engine performance and pollutant emission levels of a city-bus gas engine operating with a wide variety of natural gases. The predictive model was based on a two-zone thermodynamic approach. They found that the laminar flame speed plays a major role in the prediction of the effects of the gas composition. Moreover, they reported that the use of this model as an analysis tool enables to compare the relative influence of MN against equivalence ratio variations regarding the CA50: a variation of 10 MN points corresponds to a variation of 0.05–0.07 point on the equivalence ratio.

Some research works have been performed for Southern California Gas Company (SoCal Gas) in order to determine exhaust emissions and fuel economy of different compressed natural gas fuel blends with various fuel MNs and WIs running under various driving cycles in light duty vehicles [47–49]. Their results demonstrated an appropriate path for future researchers to pursue their investigations on natural gas fueled engines.

The performance and emission characteristics of a CNG engine were experimentally investigated under different natural gas compositions by Ha et al. [50]. They found that when the higher heating value (HHV) of the fuel gas was reduced, the average power and thermal-efficiency reductions were increased, respectively. Their results also showed that emissions of CO_2, CO, and NO_x decreased as the HHV of the fuel gas was lowered. On the other hand, the emissions of THC were not consistent, and the extent of change in their emissions was small.

Karavalakis et al. [51] investigated the implications of natural gas composition on the gaseous pollutants, fuel economy, and the



		GN	G20	C2	C3
Methane	(vol. %)	92	100	90	93
Ethane	(vol. %)	6.3		10	
Propane	(vol. %)	0.7			7
Butane	(vol. %)	0.1			
Nitrogen	(vol. %)	0.9			
Mol. weight	(g/mol)	17.27	16.04	17.45	18.01
LHV	(kJ/kg)	48956	50048	49615	49383

Fig. 4. Mass fraction burned and combustion rate versus crank angle degrees for φ=0.65 at 2000 RPM [45].

engine power output of two light-duty vehicles (a 2002 Ford Crown Victoria and a 2006 Honda Civic GX) operated over different driving cycles (Federal Test Procedure and Unified Cycle). The results of their study revealed that for modern light-duty NGVs, fuel properties have a clear and direct impact on fuel economy and some emissions components, such as CO_2 and NMHC, but not for other emission components, such as THC, NO_x, and CO. The results showed that the gases with the higher energy contents provided better fuel economy on a volumetric basis and some higher power levels. Changes in CO_2 depended on the fuel/cycle/vehicle, but, generally, blends with heavier hydrocarbons and lower H/C ratios, had higher CO_2 emissions. THC emissions showed higher emissions for the fuel with the higher levels of methane for the Crown Victoria, but no trends for the Honda. CO emissions were higher for the two fuels with the highest WNs for the Honda under same test conditions, including the cold-start phases of the driving cycles, but did not show significant fuel differences for the Crown Victoria. Changing fuel composition impacted NO_x emissions showed only limited fuel effects for the two vehicles.

Kakaee et al. [52] studied the effects of six different natural gas compositions on the combustion and emission characteristics of EF7 CNG engine using GT-POWER software. They measured engine power, torque, BMEP and BSFC under steady state operation conditions at full load conditions. They proposed a correlation between the MN and engine power to estimate engine power when the composition of natural gases varies. Javaheri et al. [53] experimentally and numerically studied the influence of natural gas composition on knocking combustion in SI gas engines using a zero-dimensional model. A SI single cylinder gas engine with variable compression ratio was used for experimental observations. Four different natural gas compositions were used for the investigations. The simulated results were in good agreement with the experimental observations.

3.2. Natural gas composition effects in CI, dual fuel and HCCI engines

There are two methods for converting diesel engine to utilize natural gas as the main fuel. The first method is to utilize compressed natural gas fully in diesel engine (known as the CNG dedicated conversion). In this method, the engine cylinder head should be changed to implement an ignition system and a CNG injector. The second method is the dual-fuel conversion using CNG as the main fuel and pilot diesel fuel to start combustion and ignite the flame of the CNG in the combustion chamber [54].

The earliest researches on evaluation of natural gas composition effect in CI engines were carried out at the beginning of 1990s. However, the main researches were done since the end of 2000s. Naber et al. [55] experimentally and computationally studied the effects of variations in natural gas composition on auto-ignition of natural gas in a DI diesel engine in a constant-volume combustion vessel. They used four fuel blends: pure methane, a capacity weighted mean natural gas, a high ethane content natural gas, and a natural gas with added propane. They found that the measured ignition delays were the longest for pure methane and became progressively shorter as ethane and propane concentrations were increased. Clark et al. [56] concluded that operation of lean-burn natural gas engines can be optimized with the implementation of a closed loop fuel control system, in terms of reducing emissions while maximizing efficiency. Such a system would compensate for variations in fuel composition, but also would correct for variations in volumetric efficiency due to

immediate engine history and long-term engine component wear. A closed loop control system on a medium-duty lean-burn engine will enhance performance by maintaining the desired air–fuel ratio to eliminate any unwanted rich or lean excursions that produce excess engine-out emissions. Such a system can also guard against internal engine damage due to overheating and/or engine knock.

Aesoy and Valland [57] investigated the influence of natural gas composition on ignition properties in a DI hot surface assisted compression ignition engine. They tested pure methane and several natural gas mixtures under various conditions in a constant volume combustion bomb and in a test engine. Ignition delay and cycle to cycle variations were used to compare the combustion qualities of the different gas. They showed that even small fractions of higher alkanes, such as ethane and propane, significantly improve ignition qualities of natural gas. In addition, ignition delay can vary by a factor of 2–3 for natural gas when compared to pure methane. They concluded that with the variable natural gas composition, engine operational parameters will need to be adjusted to compensate aggravating ignition qualities, in order to prevent efficiency loss or even ignition failure.

Graboski et al. [58] used five different natural gas fuels to determine the effect of natural gas composition and altitude on regulated emissions and performance of a Cummins B5.9G engine. The engine was a lean-burn, closed loop control, spark ignited, dedicated natural gas engine. Their results indicated that net energy based fuel economy was not effected by fuel composition. CO and PM emissions were unaffected by fuel gas composition. NO_x emissions were also unaffected by fuel composition. THC trends downwards with increasing fuel heating value. No such trend is observed for NMHC. Results acquired at altitude were compared to results obtained at 152 m (500 ft). Moreover, the test results showed rated horsepower and peak torque could be achieved at high altitude. Wide open throttle torque at speeds below peak torque speed was approximately 20% lower than at sea level, which is in proportion to the difference in barometric pressure. Emissions of PM, NOx, and NMHC were not affected by operation at altitude. Emissions of CO were slightly increased at altitude. Emissions from this engine are below all current or proposed standards for heavy duty engines on all fuels tested at both high and low altitudes. Agarwal and Assanis [59] numerically investigated the effect of natural gas composition on ignition delay by using detailed and reduced chemical kinetic mechanisms. They analyzed three different blends of natural gas at pressures and temperatures that are typical of top dead center conditions in compression ignition engines. Their computations results revealed a strong dependence of ignition delay on natural gas composition, with pure methane having the highest delay, followed by blends with increasing percentages of higher hydrocarbons.

Nigro et al. [60] tested different gaseous fuel compositions available in Brazil to evaluate performance, exhaust emissions and knock-limited spark timing in a Mercedes Benz M366G gas engine. The experimental results were correlated with methane and Wobbe numbers calculated from the gas composition. They showed that the Wobbe number of the gas is the most important fuel property among those influencing emissions and performance of lean-burn engines that use open loop fuel metering systems. On the other hand, the methane number did not affect the performance and emissions so significantly as the Wobbe number, as long as its value is high enough to avoid knocking. Mbarawa [61] investigated numerically the combined effect of natural gas composition and pilot diesel fuel injection pressure on the dual-fuel (DF) combustion of the NG–air mixture under constant-volume conditions. The used four NG compositions with air ignited by the pilot diesel spray injected at the different injection pressure and showed that an increase of ethane in the NG mixture leads to an increase in the NG burning. Furthermore, higher injection pressure improves the DF combustion processes and the pilot diesel fuel spray should be injected at higher pressure while the low-level ethane concentration in the NG composition should be kept as high as possible.

Feist [62–64] performed a series of experimental investigations to determine the feasibility of operating heavy-duty natural gas engines over a wide range of fuel compositions by evaluating engine performance and emission levels. Heavy-duty compressed natural gas engines from various engine manufacturers, spanning a range of model years and technologies including a 2007 model year Cummins ISL G, a 2006 model year Cummins C Gas Plus, a 2005 model year John Deere 6081H, a 1998 model year Cummins C Gas, and a 1999 model year Detroit Diesel Series 50G TK were evaluated using a diversity of fuel blends. Performance and regulated emission levels from these engines were evaluated using natural gas fuel blends with varying methane number ranged from MN 75 to MN 100. The authors found that all lean burn engines showed increased NO_x and HC emissions with higher WN fuels, while the stoichiometric engines showed no clear trends for NO_x or HC emissions with the various fuels. They also found that PM and CO emissions showed no strong trends with MN or WN, and that low WN fuels resulted in greater fuel consumption.

Kim et al. [30] corroborated the effect of fuel composition on the combustion and emission characteristics of a CNG engine, retrofitted from an IDI diesel engine. They used six different gas compositions as depicted in Table 4. They showed that the CNG composition had a significant influence on engine performance, fuel economy, and burning rate. They also found that there are many other factors (e.g. spark timing) beyond fuel composition that affect the combustion and emission characteristics of a CNG engine. If such factors could be controlled, the WN could be used to understand how those characteristics change depending on the change in fuel composition.

As shown in Fig. 5, the power and torque varies as a function of the engine speed (RPM) and fuel composition. The maximum torque for all gases was observed at an engine speed of 2200 RPM. It should also be noted that the torque data at both high and low RPM values varied significantly with gas composition. Likewise, the maximum power was observed at an engine speed of 3400 RPM.

As can be seen in Fig. 6, the BSFC increases for all of the gases as the engine speed increases. The BSFC is expected to be inversely proportional to the WI values of the gas. Moreover, regarding the relationship

Table 4
Compositions and properties of test fuels [30].

	Gas A	Gas B	Gas C	Gas D	Gas E	Methane gas F
CH_4	87.6	90.09	91.64	93.49	96.96	100
C_2H_6	8.4	6.04	1.93	5.08	2.6	0
C_3H_8	3.48	2.54	5.65	1.16	0.3	0
i-C_4H_{10}	0.42	0.54	0.16	0.08	0.07	0
n-C_4H_{10}	0.54	0.58	0.1	0.11	0.05	0
i-C_5H_{12}	0.02	0.02	0	0.01	0.01	0
n-C_5H_{12}	0.01	0	0	0.01	0	0
N_2	0.07	0.19	0.42	0.06	0.01	0
Propylene	–	–	0.1	–	–	–
Total	100	100	100	100	100	100
HHV	10835.3	10549.8	10500.8	10096.4	9781.3	9523.4
LHV	9798.5	9532.3	9487.3	9109	8814.8	8574.1
SG	0.645	0.627	0.626	0.594	0.573	0.555
WN	12201	12,040	11,991	11,814	11,650	11,510
CP	42.1	41.5	40.7	41.4	40.8	40.3
MON	118.8	121.9	122.1	125.3	134.3	140
MN	68.3	72.7	73.1	77.7	90.7	100
Density	0.834	0.81	0.809	0.769	0.74	0.717

between THC emissions and WI, THC emissions increase with a decrease in WI. Fig. 6(c) demonstrates that NO_x emissions increase with increasing engine speed for all fuels due to the activation of combustion. The NO_x emissions rate can also be correlated with WN, since the gas temperature is related to the WN. The lowest overall NO_x emissions rate over the whole RPM range was observed with Gas D, which may be attributable to the relatively precise spark timing. It was also found that emission characteristics at partial load are affected by the WN, fuel composition, spark timing, and burning velocity.

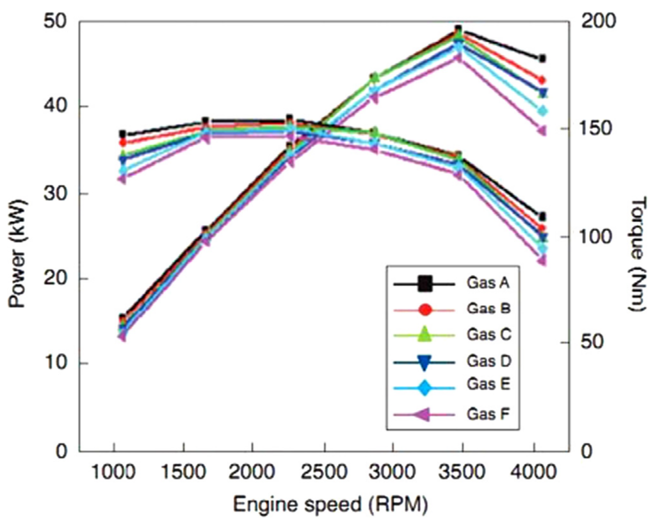


Fig. 5. Effect of gas composition on the CNG engine power and torque characteristics at WOT condition [30].

McTaggart-Cowan et al. [65] added ethane or nitrogen to a gaseous fuel to study their effects on the ignition and combustion of a non-premixed high-pressure methane–air jet. The results were used to interpret the performance of a pilot-ignited natural gas engine fueled with similar fuels. They showed that the influence of the additives on the gaseous jet ignition process is relatively small, but they have a greater effect on the research engine, where both fuels have similar influences on the spatial relationship between the gaseous jet and the pilot flame. They further investigated the implications of natural-gas composition on the combustion in a heavy-duty natural-gas engine and on the associated pollutant emissions. They reported the effects of adding ethane, propane, hydrogen, and nitrogen to the fuel. Their results indicated that these additives had no significant effect on the engine's power or fuel consumption. Emissions of unburned fuel were reduced for all additives through either enhanced ignition or combustion processes. Black carbon particulate matter emissions were increased by ethane and propane, but are virtually eliminated by including nitrogen or hydrogen in the fuel [66].

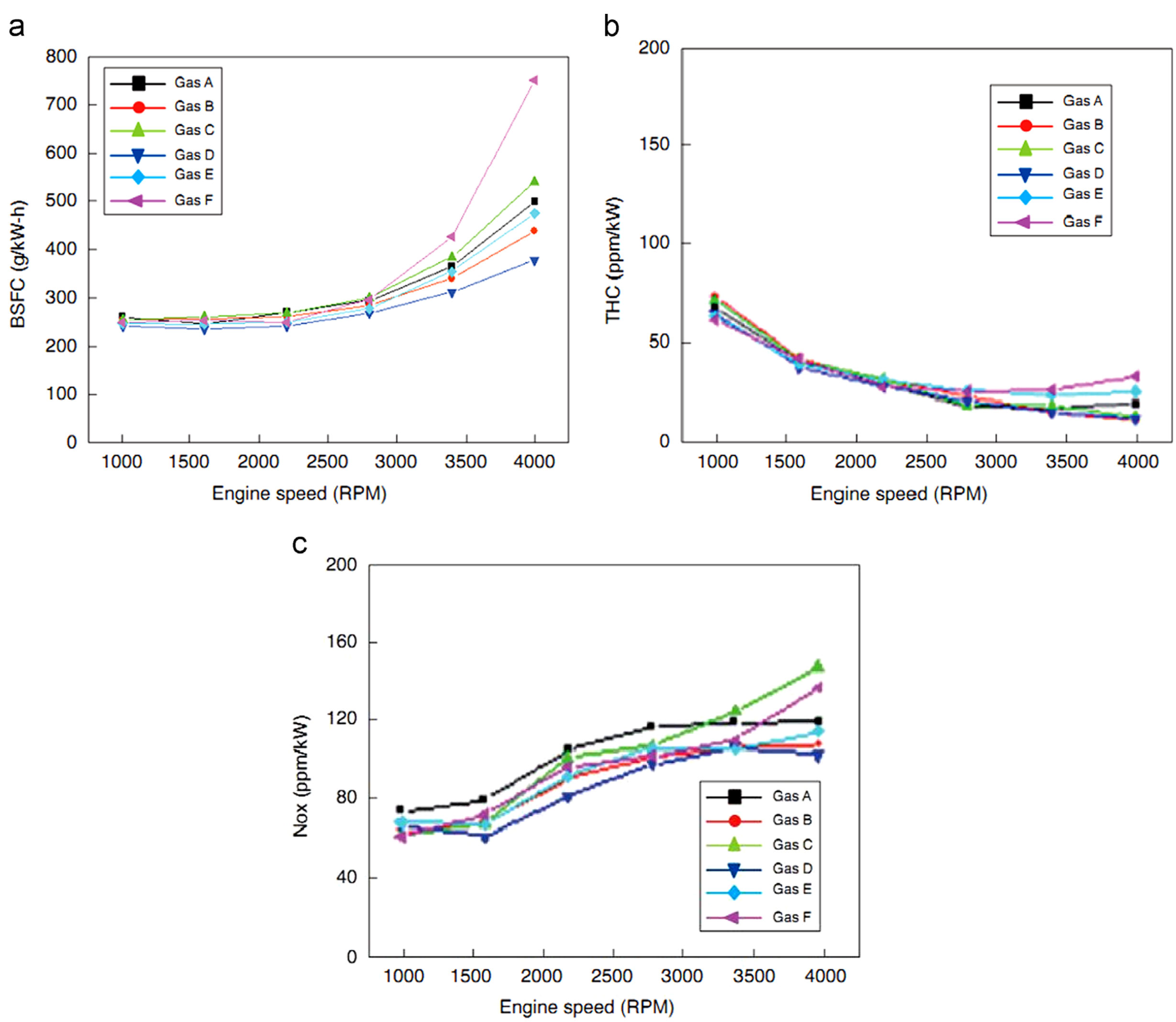


Fig. 6. Effect of fuel composition and engine speed on (a) BSFC; (b) THC emissions; (c) NO_x emissions at partial load [30].

Vavra et al. [67] computationally and experimentally investigated the influence of various levels of hydrocarbons and hydrogen in a mixture with methane at full load and different engine speeds on a light duty turbocharged stoichiometric spark ignited truck engine with a wastegate turbocharger and cooled exhaust gas recirculation (EGR). Fig. 7 shows the relative change in BMEP, thermal brake efficiency, specific CO_2 emissions and effective on-board energy (EOBE) using isolines of constant knock intensity of 2 V. Due to the necessary retarding of the spark at medium engine speed, the engine power and efficiency drop with increasing fraction of fuel additive for all cases. This retarded ignition timing causes a decrease in engine efficiency even at low load. Therefore, knock resistance is a very important quality of a fuel.

Karavalakis et al. [68,69] conducted further investigations on the impact of varying natural gas composition on exhaust emissions from a waste hauler equipped with a Cummins 8.3L, C Gas Plus, lean burn, spark ignited natural gas engine and an oxidation catalyst while operated on the William H. Martin Refuse Truck Cycle (RTC) on a chassis dynamometer as well as a bus fitted with the same engine over the central business district (CBD) cycle. The vehicle was tested on seven different fuel gas blends with varying compositions of light hydrocarbon species and inerts (Table 5), resulting in different properties in terms of MN and WN. They realized that the higher hydrocarbon gases exhibited higher fuel economy and CO_2 emissions. They reported that NO_x emissions were also impacted by fuel composition, and increased for gases with higher levels of heavier hydrocarbons. THC, CH_4, CO, PM, and particle number emissions all showed some reductions for the gases with higher hydrocarbons, higher WNs, and higher energy content.

Their results are illustrated in Fig. 8. They indicated that the higher WN test gases exhibited higher fuel economy on an energy equivalent basis compared to the CNG1, CNG2, and CNG7 blends. Significant increases in fuel economy were also observed comparing CNG3, CNG4, and CNG6 gases to CNG1, CNG2, and CNG7. The results for CO_2 emissions showed all of the fuel gas blends exhibited statistically significant increases in CO_2 emissions

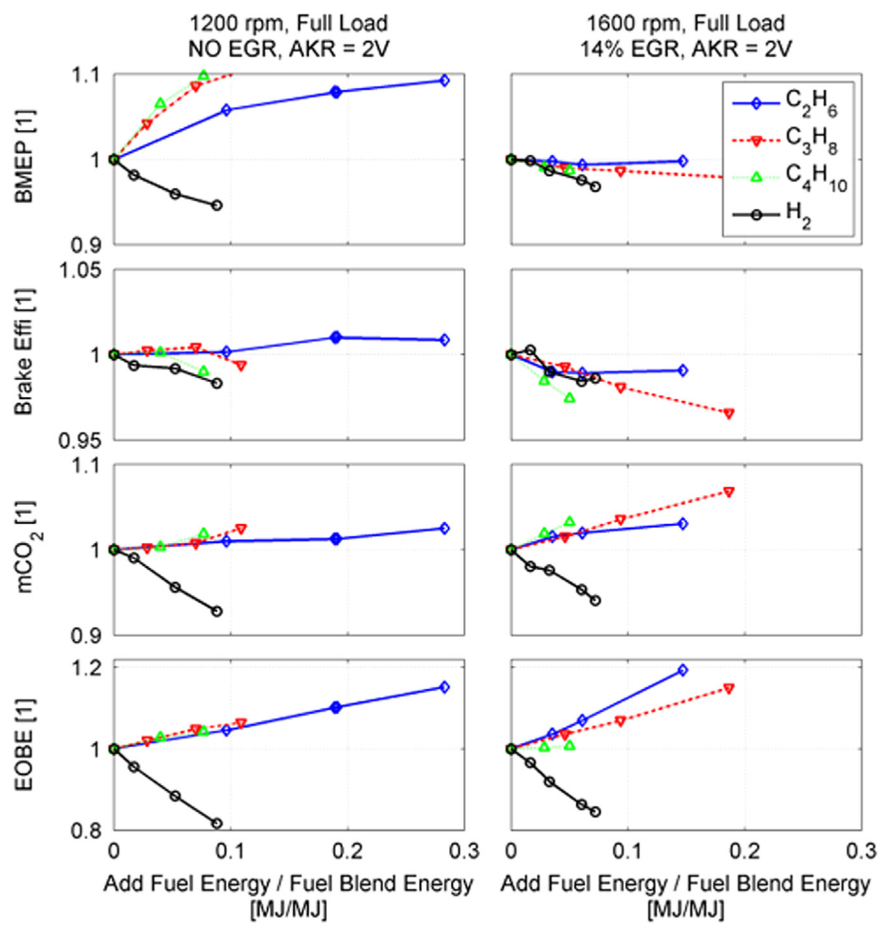


Fig. 7. Comparison of effect of various fuels addition on engine performance and specific CO_2 emissions, plots of constant knock intensity [67].

Table 5
Main properties of the natural gas fuels [68].

Gas#	Description	Methane	Ethane	Propane	I-butane	N_2	CO_2	MN	WN	HHV	H/C ratio
1	Texas pipeline (baseline gas)	96	1.8	0.4	0.15	0.7	0.95	99	1339	1021	3.94
2	Rocky mountain pipeline (baseline gas)	94.5	3.5	0.6	0.3	0.35	0.75	95	1361	1046	3.89
3	Peruvian LNG	88.3	10.5	0	0	1.2	0	84	1385	1083	3.81
4	Middle East LNG-untreated	89.3	6.8	2.6	1.3	0	0	80	1428	1136	3.73
5	Associated high ethane	83.65	10.75	2.7	0.2	2.7	0	75.3	1385	1115	3.71
6	Associated high propan	87.2	4.5	4.4	1.2	2.7	0	75.1	1385	1116	3.70
7	L-CNG fuel	98.4	1.2	0.3	0	0	0	103.1	1370	1029	3.96

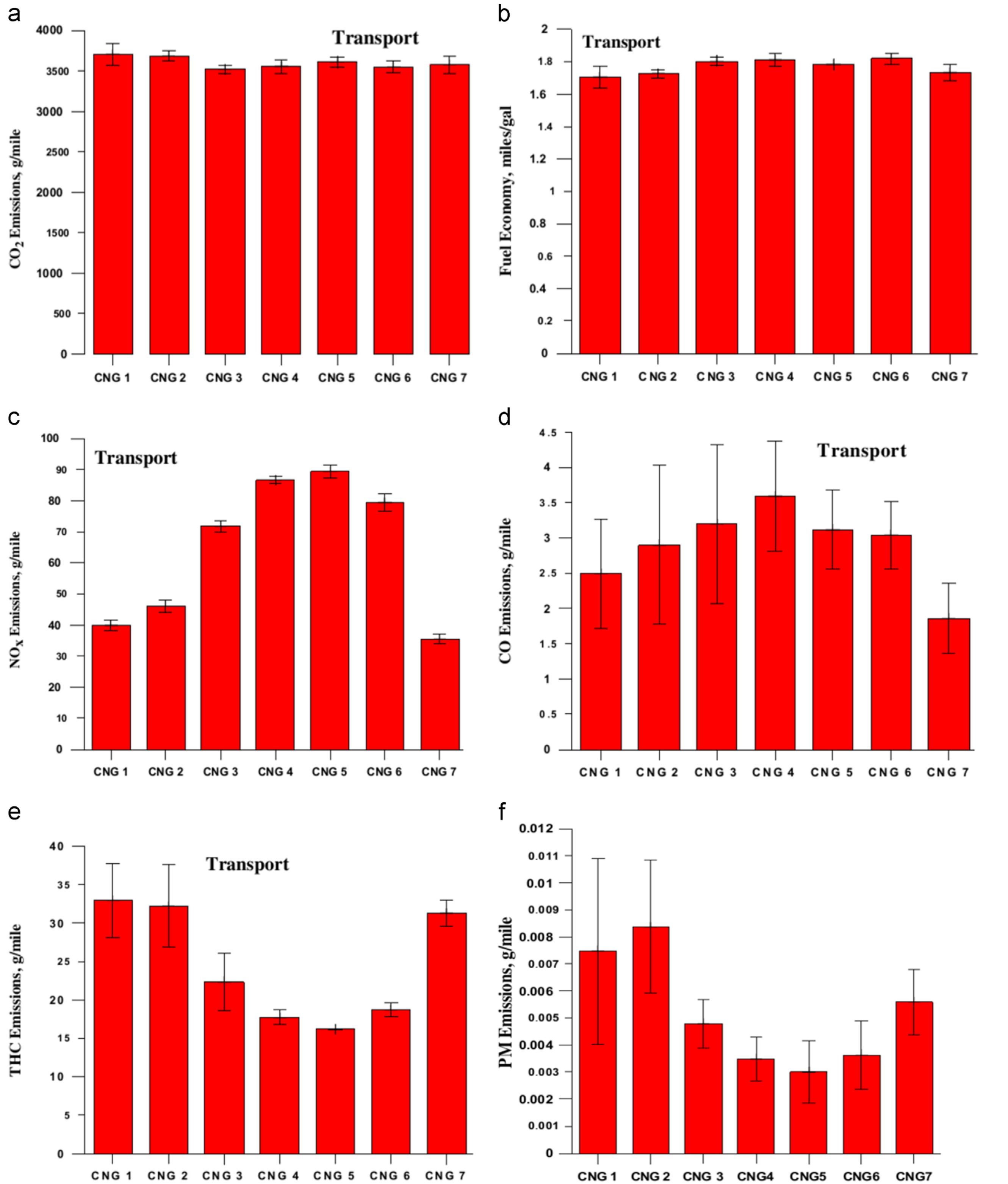


Fig. 8. (a) Average CO2 emissions, (b) average fuel economy/consumption, on a gasoline gallon energy equivalent gallon basis, (c) average NO_x emissions, (d) average CO emissions, (e) average THC emissions, (f) average PM emissions over the RTC [68].

compared to the baseline CNG1 and CNG7. Emissions of NO_x are a key concern for heavy-duty engines and can be affected by the MN and the WN. Under their test conditions, fuel composition had a significant influence on NO_x emissions, as shown in Fig. 8(c). Generally, NO_x emissions demonstrated an increase as MN was decreased and WN was increased during all the RTC. Their results are in line with data reported in previous publications showing that NO_x emissions increased with the mixture energy content. As shown in Fig. 8(d), it is evident that CO emissions were generally higher with CNG4, CNG5, and CNG6 gases when compared to other blends. Also, THC emissions followed the same pattern as depicted in Fig. 8(e). The gases containing higher hydrocarbons and having lower methane numbers,

such as CNG3, CNG4, CNG5, and CNG6, produced lower THC emissions than the baseline CNG1 and CNG2 and CNG7 gases.

A major source of PM in natural gas engines is the engine lubricating oil. In addition, fuel composition and molecular structure influence PM emissions. Natural gas is a gaseous fuel, unlike gasoline and diesel, which more readily mixes during combustion, reducing the formation of fuel-rich zones. Hence, its combustion will likely produce the lowest PM emissions levels. They measured PM mass emissions for the RTC and it was very low, as shown in Fig. 8(f). Considerable reductions in PM emissions were found for CNG4, CNG5, and CNG6 compared to CNG1, CNG2, and CNG7. CNG3 also demonstrated statistically significant reductions relative to CNG1 and CNG2, but not compared to CNG7. This was consistent with the trends seen for CO and THC emissions on the waste hauler, with the gases with higher hydrocarbons resulting in PM reductions, while the gases with high methane numbers resulting in higher PM levels [68].

Hajbabaei et al. [70] studied the effects of varying natural gas composition on the exhaust emissions from different technology transit buses. They used two CNG buses equipped with lean burn

Table 6
Different blends of natural gas [77].

	Gas A	Gas B	Gas C	Gas D	Gas E	Gas F
CH_4	100	99	97.5	95.85	90.6	88.7
C_2H_6	0	0	2	3.44	6.54	7.2
C_3H_8	0	1	0.5	0.71	2.66	3.6
N_2	0	0	0	0	0.2	0.5
Molar weight	16.04	16.32	16.46	16.72	17.73	18.12
LHV (MJ/kg)	50.03	49.93	49.89	49.80	49.35	49.02
SG	0.553	0.563	0.568	0.577	0.612	0.626
WN	43.81	44.11	44.26	44.53	45.43	45.63
Note	Pure methane	Methane/propane blend	Methane/ethane blend	Common in USA	Common in South Korea	Common in Iran

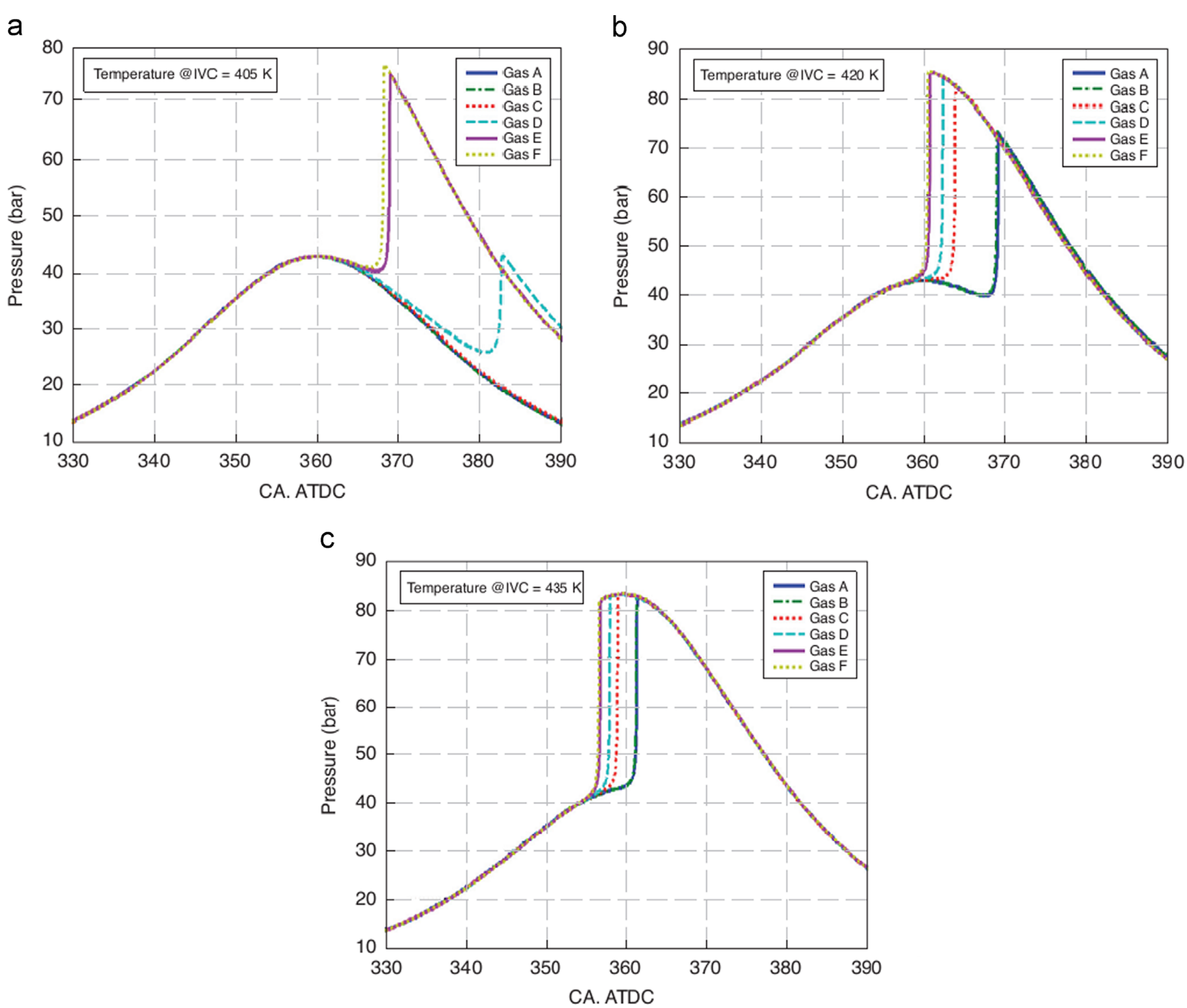


Fig. 9. Pressure trend near TDC for different gas fuels at different initial temperature [77].

combustion and oxidation catalysts (2004 John Deere 8.1L 6081H and 2003 8.3L Cummins Westport C-Gas Plus), and one stoichiometric CNG bus equipped with a TWC and EGR (Cummins Westport ISL-G8.9L engine) were tested on a chassis dynamometer over the CBD cycle on six different gas blends each. They found that for the lean burn buses, gases with low methane contents exhibited higher NO_x and NMHC emissions, but lower emissions of THC, CH_4 and formaldehyde emissions. The stoichiometric engine bus with a TWC showed significantly reduced NO_x and THC emissions compared to the lean burn buses, but did show higher levels of CO and NH_3. PM mass emissions did not show any fuel effects, while particle number (PN) emissions exhibited some reductions for the higher WN gases.

HCCI is a type of premixed compression ignition combustion that has been shown to have superior characteristics in terms of thermal efficiency due to lower heat transfer losses and shorter combustion durations, and reduced engine out NO_x and PM emissions resulted from the lean, low temperature combustion process. In HCCI, the fuel and air mixture is prepared externally from the cylinder and is inducted as a homogeneous charge. Then, the homogenous mixture is subjected to the appropriate initial thermodynamic conditions as a function of engine speed, equivalence ratio, inlet temperature and pressure. Afterwards, auto-ignition occurs across the entire cylinder [71–73]. Natural gas is well-suited to the HCCI combustion concept because of minimal mixture preparation requirements and chemical stability [74].

Although HCCI combustion has attracted the researchers in the last decade, a few research works have been published in the literature. Fiveland et al. [75] studied the influence of natural gas composition on engine operation both experimentally and through chemical kinetic based cycle simulation. A range of two component gas mixtures has been tested with methane as the base fuel. For each fuel mixture, the start of combustion was phased TDC and then the inlet mixture temperature was reduced. Their reported results clearly demonstrate the ability of a thermo-kinetic, single-zone model to capture the fuel composition effects seen in the experiments. Flowers et al. [76] examined the effect of natural gas composition on HCCI combustion, and then explored three control strategies for HCCI engines: DME (dimethyl ether) addition, intake heating and hot EGR addition. They showed that HCCI combustion is sensitive to natural gas composition, and an active control may be required to compensate for possible changes in composition. In addition, each control strategy has been evaluated for its influence on the performance of an HCCI engine

The influence of natural gas composition on engine operation in HCCI mode was studied by Jahanian and Jazayeri [77]. Six different compositions of natural gas (Table 6) have been considered to study the engine performance via a thermo-kinetic zero-dimensional model. Their results indicated that the peak value of pressure/temperature of in-cylinder mixture is dependent of fuel WN. Furthermore, engine gross indicated power was linearly related to fuel WN. Gross indicated work, gross mean effective pressure, and NO_x were the other parameters utilized to compare the performance of engine using different fuel compositions.

Fig. 9 shows pressure trend near TDC for different fuel types in three different initial temperatures. Although the main component of NG is methane, but usually the start of combustion in NG HCCI engines depends on other components such as ethane and propane, which ignites earlier in lower temperature. Existence of heavier hydrocarbons in NG leads to auto-ignition in such a condition that pure methane does not ignite. This figure shows that while fuels with high content of methane (Gases A–C) do not ignite; other fuels that have more ethane and propane in their composition will ignite. By increasing initial temperature, all fuels will ignite with different SOC. It can be concluded that fuels with more propane contents ignite earlier.

The maximum temperature of in-cylinder mixture for different gas fuels at different engine speeds is shown in Fig. 10. Increasing engine speed causes a small variation in the maximum temperature/pressure of all fuels except Gases A and B, which show a sharp decrease and undergo an abnormal late combustion. However, it should be mentioned that the engine speed variation is relatively small. It can be seen that there is a meaningful relation between fuel WN and the value of maximum pressure/temperature. The fuels with higher WN ignite earlier and have higher peak in temperature/pressure diagram. By increasing engine speed from 700 to 1100 RPM, the crank angle that peak pressure occurs at, changes about 2.2 CA for Gas F but Gas A has wide variation of about 11.5 CA.

Simulated NO_x emission from the engine is shown in Fig. 11. The main source of NO_x in HCCI engines is thermal NO_x; so it is obvious that the amount of NO_x is directly related to in-cylinder temperature trend. Two parameters affect this relation:

– maximum cylinder temperature;
– duration of high temperature.

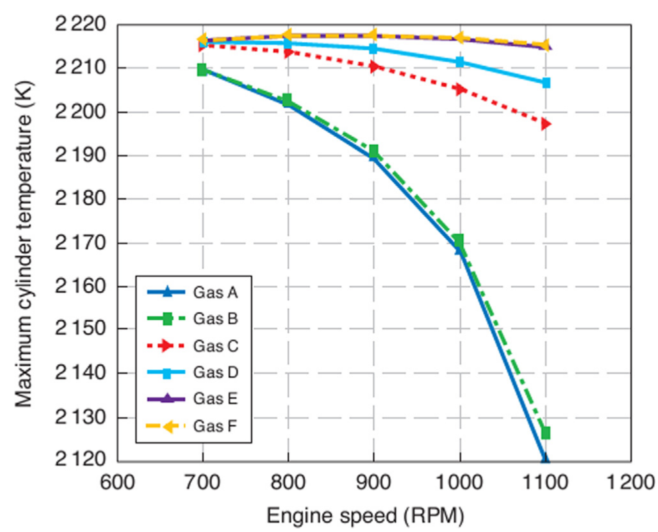


Fig. 10. Maximum cylinder temperature for different gas fuels [77].

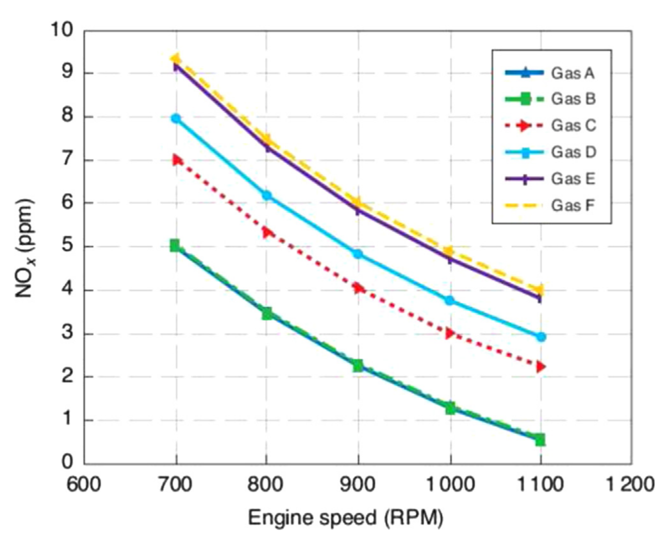


Fig. 11. NO_x emission for different gas fuels [77].

In comparison of different compositions, the first parameter is important. The fuels with high WN make high in-cylinder temperature and therefore higher NO_x is expected.

Gross indicated power shows a linear relation to fuel WN at selected range of engine speed. It can be defines as

$$\text{Engine power} = C_1\ \text{WN} + C_2 \tag{5}$$

It is practical to use cubic curve fitting in order to acquire the relation between C_1–C_2 and engine speed (N) [77],

$$C_1 = 0.004399(N/100)^3 - 0.10272(N/100)^2 + 0.81409(N/100) - 2.1828$$

$$C_2 = -0.1998(N/100)^3 - 0.4.6655(N/100)^2 - 36.309(N/100) + 98.584 \tag{6}$$

Table 7 summarizes the main research works on implication of natural gas composition in ICEs.

4. Summary and conclusions

A detailed review of the influence of natural gas composition on the combustion and emission characteristics natural gas fueled internal combustion engines were presented in this paper and the main results obtained were reported. First the natural gas composition was explained and the required information was described. Then, the effects of natural gas composition on the performance and emission characteristics of SI, CI, dual fuel and HCCI engines were reviewed. The researchers unanimously stated that the principal natural gas fuel properties were the heating value, the energy density per cycle, the Wobbe number, methane number, and the combustion potential. According to the literature review, the majority of research has been focused on lean burn SI engines, which are currently the predominant form of natural-gas engines. In SI engines, it was generally described by the researchers that natural gas fuel properties have a clear and direct effect on fuel

Table 7
Main research works on implication of natural gas composition in ICEs.

Researchers (time)	Experimental equipment or numerical approaches	Test conditions	Gas compositions	Research objects
Elder et al. [37]	4 Cylinder, four stroke, SI engine	Vehicles have been run on a chassis dynamometer over the urban cycle of NZS 5420:1980 at steady speeds of 50 km/h and 80 km/h	Two LPG fuels and two CNG fuels	Fuel consumption, power output and pollutant emissions
Naber et al. [55]	A constant-volume combustion vessel and a fuel injection system	CR: 23:1, core temperatures from 900 to 1600 K	Four NG gas compositions	Auto-ignition of natural gas
Matthews et al. [40]	GM 3/4-ton pickup, a Ford passenger car and a full size Dodge van	All tests were performed using the Federal Test Procedure (FTP) driving cycle	Four different compositions of NG	Effects of NG composition on emissions, fuel economy, and driveability
Agarwal et al. [59]	Numerical simulation using detailed and reduced chemical kinetic mechanisms	–	Three different compositions of NG	Effect of natural gas composition on ignition delay
Lee et al. [42,43]	DOHC 4 Cyl. & SOCH 4 Cyl.	FTP-75 cycle	Six different gas compositions	Vehicle performance such as fuel economy, driveability and exhaust emissions
Caillol et al. [45]	Single-cylinder, 4 stroke, SI engine, Bore: 67 mm, Stroke: 51 mm, CR: 8.5:1 one-zone approach using CHEMKIN II	Wide-open throttle (WOT) and full load conditions at a constant speed (2000 RPM)	Three different compositions of CNG	Influence of the fuel mixture composition on mass burn rates and burning velocities
Min et al. [44]	1.5-L gasoline engine	WOT condition with the engine speeds of 2000 RPM and 3500 RPM. The A/F ratio and spark timing were controlled to obtain the MBT condition for each gas fuel.	Eight gas compositions	Engine performance and emission characteristics
Kim et al. [30]	2.5 L, 4-cylinder CNG engine, retrofitted from an IDI diesel engine	WOT and the partial load conditions, Spark timing on the MBT	Six gas compositions	Combustion and emission characteristics
McTaggart-Cowan et al. [65,66]	Cummins ISX series modified for single-cylinder operation	Mid-load operating condition, EGR=30%, pilot diesel and gaseous-fuel rail pressures were constant at 21 MPa	Ten gas compositions	Ignition and combustion of a non-premixed high-pressure methane-air jet, combustion in a heavy–duty natural- gas engine pollutant emissions
Feist et al. [64]	2007 Model year Cummins ISL G, a 2006 model year Cummins C Gas Plus, a 2005 model year John Deere 6081H, a 1998 model year Cummins C Gas, and a 1999 model year Detroit Diesel Series 50G TK	Engines were operated in a durability test cell for engine break-in and catalyst aging as well as a transient test cell for performance and emissions testing.	Five gas compositions	Effect of gas composition on engine performance, as well as engine power levels, overall engine operability and exhaust emissions
Varva et al. [67]	Avia, four cylinder, 4 stroke, CI engine, Bore: 102 mm, Stroke: 120 mm, CR: 12:1	Full load and various engine speeds	Mixtures of ethane, propane and butane with a pipeline NG within the range of volumetric fractions	Impact of fuel composition on engine performance by continuously increasing the concentration of a single additive
Karavalakis et al. [51]	2006 Model year Honda Civic GX and a 2002 model year Ford Crown Victoria	Federal Test Procedure (FTP) and three Unified Cycle (UC)	Seven compositions	Gaseous pollutants, fuel economy, and the engine power output
Jahanian et al. [77]	Zero-dimensional single zone thermo-kinetic model with MATLAB®, CANTERA® module	HCCI combustion mode	Six gas compositions	Combustion pressure/temperature, gross indicated power NO_x
Karavalakis et al. [68,69]	2003 Cummins 8.3L C Gas Plus, lean burn	William H. Martin refuse truck driving cycle and central business district (CBD) test cycle	Five and seven gas compositions	Gaseous pollutants, fuel economy, and the engine power output
Hajbabaei et al. [70]	2004 John Deere 8.1L 6081H and 2003 8.3L Cummins Westport C-Gas Plus and Cummins Westport ISL-G8.9L engine	central business district (CBD) cycle	Six gas compositions	Exhaust emissions
Kakaee et al. [52]	1-D simulation using GT-POWER	WOT and full load conditions at varying engine speed	Six gas compositions	Combustion and emission characteristics

economy and some emissions, such as CO_2 and NMHC, but not for other emission, such as THC, NO_x, and CO. The fuel economy was proportional to lower heating value of stoichiometric unit mixture. The results obtained highlighted that the gases with the higher energy contents provided better fuel economy on a volumetric basis and some higher power levels. Regarding the tailpipe emissions, effects of gas composition on CO, NO_x, and THC emissions did not show a clear trend. THC decreased with increasing WI and CP. On the other hand, it was observed that CO_2, CO, NO_x increases as WI and CP increase. On contrary, some researchers reported that THC, CH_4, CO, PM, and particle number emissions are reduced for the gases with higher hydrocarbons, higher Wobbe numbers, and higher energy content. In addition, gas composition variation had a negligible effect on vehicle driveability.

In CI engines, some authors reported that NO_x and HC emissions were increased with higher Wobbe number fuels and PM and CO emissions showed no strong trends with Wobbe number variation. It was also reported that the in-cylinder pressure was proportional to the WI and exhaust emission characteristics were affected by the WI, fuel composition, spark timing, and burning velocity. Furthermore, it was indicated that adding ethane, propane, hydrogen, and nitrogen to the fuel had no significant effect on the engine's power or fuel consumption. Emissions of unburned fuel were reduced for all additives and PM emissions were increased by ethane and propane, but are virtually eliminated by including nitrogen or hydrogen in the fuel. In HCCI engines, it was stated that the peak value of pressure/temperature of in-cylinder mixture was depending on fuel WN and engine gross indicated power was linearly related to fuel WN. Moreover, fuels with high WN make high in-cylinder temperature and therefore higher NO_x emissions.

For future work, there is a need for detailed experimental and numerical studies of natural gas composition effects in ICEs particularly in advanced combustion engines with low temperature combustion (e.g. dual fuel reactivity controlled compression ignition combustion). For instance the turbulent flame speed, flame propagation characteristics, and emissions generation characteristics of natural gas at various operating conditions and with combination with other alternative fuels should be addressed. The effects of inlet conditions such as EGR or hydrogen (to accelerate combustion progress) are even less well known in natural gas fueled engines. Combinations of effects of different performance parameters (such as compression ratio, equivalence ratio, ignition timing for lean burn SI engines or fuel-injection timing for dual-fueled CI engines with NG) on combustion and exhaust emissions of natural gas engines are not well known. As a result, there must be abundant works and achievements from the researches on this field that should come to the world in future.

References

[1] IEO, Natural gas trends. 〈http://www.eia.doe/iea/overview.html〉 [accessed May 2003].

[2] Economides MJ, Wood DA. The state of natural gas. J Nat Gas Sci Eng 2009;1(1–2):1–13.

[3] Malenshek M, Olsen DB. Methane number testing of alternative gaseous fuels. Fuel 2009;88:650–6.

[4] Mctaggart-Cowan GP, Jones HL, Rogak SN, Bushe WK, Hill PG, Munshi SR. The effects of high pressure injection on a compression ignition, direct injection of natural gas engine. ASME J Eng Gas Turbines Power 2007;129:579–88.

[5] Ibrahim A, Saiful B. A comparison between EGR and lean-burn strategies employed in a natural gas SI engine using a two-zone combustion model. Energy Convers Manag 2009;50:3129–39.

[6] Abdelaal MM, Hegab AH. Combustion and emission characteristics of a natural gas-fueled diesel engine with EGR. Energy Convers Manag 2012;64:301–12.

[7] Bakar Abu, Kadirgama R, Rahman K, Sharma MM, Semin KV. Application of natural gas for internal combustion engines. Advances in natural gas technology. Dr. Hamid Al-Megren, InTech; 2012.

[8] Wang-Helmreich H, Lochner S. The potential of natural gas as a bridging technology in low-emission road transportation in Germany. Therm Sci 2012;16(3):729–46.

[9] Richards GA, McMillian MM, Gemmen RS, Rogers WA, Cully SR. Issues for low-emission, fuel-flexible power systems. Prog Energy Combust Sci 2001;27:141–69.

[10] McTaggart-Cowan GP, Reynolds CCO, Bushe WK. Natural gas fuelling for heavy-duty on-road use: current trends and future direction. Int J Environ Stud 2006;63:421–40.

[11] Korakianitis T, Namasivayam AM, Crookes RJ. Natural-gas fueled spark ignition (SI) and compression-ignition (CI) engine performance and emissions. Prog Energy Combust Sci 2011;37(1):89–112.

[12] Shamekhi AH, Khatibzadeh N, Shamekhi A. A comprehensive comparative investigation of compressed natural gas as an alternative fuel in a bi-fuel spark ignition engine. Iran J Chem Chem Engineering 2008;27(1):73–83.

[13] Kakaee AH, Paykani A. Research and development of natural gas fueled engines in Iran. Renew Sustain Energy Rev 2013;26:805–21.

[14] Paykani A, Khoshbakhti Saray R, Shervani-Tabar MT, Mohammadi-Kousha A. Effect of exhaust gas recirculation and intake pre-heating on performance and emission characteristics of dual fuel engines at part loads. J Cent S Univ 2012;19(5):1346–52.

[15] Hesterberg TW, Lapin CA, Bunn WB. A comparison of emissions from vehicles fueled with diesel or compressed natural gas. Environ Sci Technol 2008;42:6437–45.

[16] Cho HM, He B-Q. Combustion and emission characteristics of a natural gas engine under different operating conditions. Environ Eng Res 2009;14(2):95–101.

[17] Jahirul MI, Masjuki HH, Saidur R, Kalam MA, Jayed MH, Wazed MA. Comparative engine performance and emissions analysis of CNG and gasoline in a retrofitted car engine. Appl Therm Eng 2010;30:2219–26.

[18] Liu Y, Yeom J, Chung S. A study of spray development and combustion propagation processes of spark-ignited direct injection (SIDI) compressed natural gas (CNG). Math Comput Model 2013;57(1–2):228–44.

[19] Natural gas vehicle statistics: NGV count – international association for natural gas vehicles; 2012.

[20] U.S. Department of Energy, Alternative Fuels Data Center, fuel properties, 〈http://www.afdc.energy.gov/fuels/properties.html〉; 2012.

[21] Demirbas A. Methane gas hydrate. London: Springer-Verlag London limited; 2010.

[22] Farzaneh-Gord M, Rahbari HR, Nikofard H. The effect of important parameters on the natural gas vehicles driving range. Pol J Chem Technol 2012;14(4):61–8.

[23] Farzaneh-Gord M, Rahbari HR, Bajelan M, Pilehvari L. Investigation of hydrate formation in natural gas flow through underground transmission pipeline. J Nat Gas Sci Eng 2013;15:27–37.

[24] Liss WL, Thrasher WH, Steinmetz GF, Chowdiah P, Attari A. Variability of natural gas composition in select metropolitan areas of the United States. Gas research institute report No. GRI-92/0123; March 1992.

[25] Blazek CF, Freeman P, Bailey BK, Colucci C. Fuel composition effects on natural gas vehicle emissions. 207th ACS national meeting-division of fuel chemistry, San Diego, USA; March 13–17, 1994.

[26] Ly H. Effects of natural gas composition variations on the operation, performance, and exhaust emissions of natural gas-powered vehicles. International conference on NGV, Washington DC; 2002.

[27] Chiu JP. Paper study on the effect of varying fuel composition on fuel supplied to Detroit Diesel gas engines. SwRI project No. 03.32.40. 10646.02; 2005.

[28] Kubesh J, King SR, Liss WE. Effect of gas composition on octane number of natural gas fuels. SAE Technical 922359; 1992.

[29] Kubesh J. Effect of gas composition on octane number of natural gas fuels. SwRI-3178-4.4, GETA 92-01, GRI-92/0150; 1992.

[30] Kim K, Kim H, Kim B, Lee K, Lee K. Effect of natural gas composition on the performance of a CNG engine. Oil Gas Sci Technol – Rev IFP 2009;64(2):199–206.

[31] IANGV, 2012. 2011 Natural Gas Vehicle Statistics, International association for natural gas vehicles. Available from: 〈http://www.iangv.org/2012/05/2011-natural-gas-vehicle-statistics-released/〉 [accessed June 2013].

[32] Aslam MU, Masjuki HH, Kalam MA, Abdesselam H, Mahlia TMI, Amalina MA. An experimental investigation of CNG as an alternative fuel for a retrofitted gasoline vehicle. Fuel 2006;85(5–6):717–24.

[33] Kalam MA, Masjuki HH. An experimental investigation of high performance natural gas engine with direct injection. Energy 2011;36:3563–71.

[34] Cho HM, He B-Q. Spark-ignition natural engines – a review. Energy Convers Manag 2007;48:608–18.

[35] Folkson R. Alternative fuels and advanced vehicle technologies for improved environmental performance. Alternative and renewable gaseous fuels to improve vehicle environmental performance. London: Woodhead Publishing Limited; 2014; 90–116(chapter 4).

[36] Khalil E, Karim G. A kinetic investigation of the role of changes in the composition of natural gas in engine applications. J Eng Gas Turb Power 2002;124(2):404–11.

[37] Elder ST, Jones K, Taine RR. Effects of varying fuel composition on the performance of CNG and LPG fueled vehicles. Trans Inst Prof Eng N Z: Electr/Mech/Chem Eng Sect 1985;12(3):161–72.

[38] King S. The impact of natural gas composition on fuel metering and engine operational characteristics. SAE Technical 920593; 1992.

[39] Thiagarajan S, Midkiff KC, Bell SR, Green MN. Investigation of fuel composition effects on a natural gas fueled spark-ignited engine. In: Proceedings of the

ASME internal combustion engine division spring meeting; Marietta, OH, USA; 1995.
[40] Matthews R, Chiu J, Hilden D. CNG compositions in Texas and the effects of composition on emissions, fuel economy, and drivability of NGVs. SAE Technical 962097; 1996.
[41] El-Sherif AS. Effects of natural gas composition on the nitrogen oxide, flame structure and burning velocity under laminar premixed flame conditions. Fuel 1998;77:1539–47.
[42] Lee Y, Kim G. Effect of gas compositions on fuel economy and exhaust emissions of natural gas vehicles. KSAE 1999;7(8):123–31.
[43] Lee Y-J, Kim G-C. Effect of gas composition on NGV performance. FISITA World Automotive Congress, SAE No. 2000-05-0169, Seoul, Korea; 2000.
[44] Min BH, Chung JT, Kim HY, Park SS. Effects of gas composition on the performance and emissions of compressed natural gas engines. KSME Int J 2002;16(2):219–26.
[45] Caillol C, Delorme T, Denis P, Berardi G, Porterie B. A combustion model for analyzing the effects of natural gas composition on the operation of a spark ignition engine. SAE technical paper 2002-01-2236; 2002.
[46] Caillol C, Berardi G. A simulation tool for evaluating gas composition effects on engine performance. In: Proceedings of the international gas research conference, Vancouver; November 1–4, 2004, p. 1–19.
[47] Liss, E William. Light duty CNG vehicle fuel composition study. Prepared for Southern California Gas Company, Topical Report, GTI Project Number 20245; April 2006.
[48] Crawford R, Lyons J. Effects of gas composition in emissions from a light-duty natural gas vehicle. Prepared for Southern California Gas Company, report No. SR2009-11-01; November 2009.
[49] Timmons S. Natural gas fuel effects on vehicle exhaust emissions and fuel economy. SwRI project No. 03-13721.01.200; January 2010.
[50] Ha YC, Lee SM, Kim BG, Lee CJ. Performance and emission characteristics of a CNG engine under different natural gas compositions. Trans Korean Soc Mech Eng, B 2011;35(7):749–55.
[51] Karavalakis G, Durbin TD, Villela M, Miller WJ. Air pollutant emissions of light-duty vehicles operating on various natural gas compositions. J Nat Gas Sci Eng 2012;4:8–16.
[52] Kakaee AH, Karimi M, Paykani A. A comparative study on influence of natural gas composition on the performance of a CNG engine. In: 8th Mediterranean combustion symposium, Çesme, İzmir, Turkey; September 8–13, 2013.
[53] Javaheri A, Esfahanian V, Salavati-Zadeh A, Darzi M, Mirsoheyli SM. Investigation of natural gas composition effects on knock phenomenon in SI gas engines using detailed chemistry. Appl Mech Mat 2014;493:239–44.
[54] Poompipatpong Ch, Cheenkachorn K, editors. Energy, 36; 2011. p. 6862–6.
[55] Naber JD, Siebers DL, Di Julio SS, Westbrook CK. Effect of natural gas composition on ignition delay under diesel conditions. Combust Flame 1994;99(2):192–200.
[56] Clark NN, Mott GE, Atkinson CM, deJong RJ, Atkinson RJ, Latvakosky T, et al. Effect of fuel composition on the operation of a lean-burn natural gas engine. SAE 952560; 1995.
[57] Aesoy V, Valland H. The influence of natural gas composition on ignition in a direct injection gas engine using hot surface assisted compression ignition. SAE technical paper, SAE 961934; 1996.
[58] Graboski MS McCormick RL, Newlin AW, Dunnuck DL, Kamel MM, Ingle WD. Effect of fuel composition and altitude on regulated emissions from a lean-burn, closed loop controlled natural gas engine. SAE Technical 971707; 1997.
[59] Agarwal A, Assanis D. Modeling the effect of natural gas composition on ignition delay under compression ignition conditions. SAE Technical 971711; 1997.
[60] Nigro F, Trielli M, Zabeu C, Silva L et al. Effects of natural gas composition on bus engine performance. SAE Technical 973038; 1997, 10.4271/973038.
[61] Mbarawa M. Numerical simulation of the combined effects of natural gas composition and pilot diesel fuel injection pressure on the dual-fuel combustion of a natural gas–air mixture under constant-volume conditions. J Energy Inst 2006;79(1):26–37.
[62] Feist MD. Fuel composition testing using DDC series 50G natural gas engines. Final report prepared by Southwest RESEARCH INSTITUTE for the Southern California gas company, report No. 11657; August 2006.
[63] Feist MD. Fuel composition testing using Cummins, John Deere, and Detroit Diesel 50G natural gas engines. Final report prepared by Southwest Research Institute for the Southern California Gas Company, report No. 03.13721; April 2009.
[64] Feist MD, Landau M, Harte E. The effect of fuel composition on performance and emissions of a variety of natural gas engines. SAE technical paper series 2010-01-1476; 2010.
[65] McTaggart-Cowan GP, Wu N, Jin B, Rogak SN, Davy MH, Bushe WK. Effects of fuel composition on high-pressure non-premixed natural gas combustion. Combust Sci Technol 2009;181:397–416.
[66] McTaggart-Cowan GP, Rogak SN, Munshi SR, Hill PG, Reynolds, Bushe WK. The influence of fuel composition on a heavy-duty, natural-gas direct-injection engine. Fuel 2010;89:752–9.
[67] Vavra J, Takats M, Klir V, Skarohlid M. Influence of natural gas composition on turbocharged stoichiometric SI engine performance. SAE technical paper 2012-01-1647; 2012.
[68] Karavalakis G, Hajbabaei M, Durbin TD, Johnson KC, Zheng Zh, Miller WJ. The effect of natural gas composition on the regulated emissions, gaseous toxic pollutants, and ultrafine particle number emissions from a refuse hauler vehicle. Energy 2013;50:280–91.
[69] Karavalakis G, Gysel N, Hajbabaei M, Durbin T, Johnson K, Miller W. Influence of different natural gas compositions on the regulated emissions, aldehydes, and particle emissions from a transit bus. SAE technical paper, 2013-01-1137; 2013. 10.4271/2013-01-1137.
[70] Hajbabaei M, Karavalakis G, Johnson KC, Lee L, Durbin T. Impact of natural gas fuel composition on criteria, toxic, and particle emissions from transit buses equipped with lean burn and stoichiometric engines. Energy 2013;62:425–34.
[71] Zhao F, Assanis DN, Asmus TN, Dec JE, Eng JA, Najt PM. Homogeneous charge compression ignition (HCCI) engines: key research and development issues. Warrendale, PA: Society of Automotive Engineers; 2003.
[72] Yao M, Zheng Z, Liu H. Progress and recent trends in homogeneous charge compression ignition (HCCI) engines. Prog Energy Combust Sci 2009;35:398–437.
[73] Akbarzadeh A, Talati F, Paykani A. Effect of radiation heat transfer on HCCI multizone combustion. Heat Transf Res 2014;45(1):23–41 (doi:10.1615Heat-TransRes. 2013003322).
[74] Jahanian O, Jazayeri SA. A numerical investigation on the effects of using formaldehyde as an additive on the performance of an HCCI engine fueled with natural gas. Int J Energy Environ Eng 2011;2(3):79–89.
[75] Fiveland SB, Christensen M, Johansson B, Hiltner J, Mauss F, Assanis DN. Experimental and simulated results detailing the sensitivity of natural gas HCCI engines to fuel composition. SAE paper 2001-01-3609; 2001.
[76] Flowers D, Dibble R, Aceves S, Westbrook CK, Smith JR. Detailed chemical kinetic simulation of natural gas HCCI combustion: gas composition effects and investigation of control strategies. J Eng Gas Turb Power 2001;123(2):433–9.
[77] Jahanian O, Jazayeri SA. A comprehensive numerical study on effects of natural gas composition on the operation of an HCCI engine. Oil Gas Sci Technol 2012;67(3):503–15.